METHOD AND APPARATUS FOR THIXOTROPIC MOLDING OF SEMISOLID ALLOYS

CROSS-REFERENCE TO RELATED APPLICATIONACHS

Continuations on U.S. patent Appl. No. 60/442,481 filed on Jan. 27, 2003.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

Not Applicable.

REFERENCE TO SEQUENCE LISTING, A TABLE, OR A COMPUTER PROGRAM LISTING APPENDIX

Not Applicable.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to an economical procedure and apparatus for molding semisolid metallic materials using a dendritic-free feedstock bar as a one-time extruder plunger to inject semisolid slurries converted from a terminal portion of the same feedstock bar.

2. Description of the Prior Art

Thixotropic molding is a relatively new metal forming process during which semisolid slurry containing round solid particles dispersed in a continuous liquid phase is converted from a feedstock alloy and subsequently injected into a mold cavity. In comparison with conventional high

pressure die-casting procedures, which work with liquid metals, thixotropic molding is capable of producing parts that are: 1) bubble free due to non-Newtonian viscosity - an inverse relationship between viscosity and the rate of shear - of the semisolid slurry and 2) less shrinkage due to the presence of a solid phase in the slurry and lower operating temperatures. It may also increase the lifetime of machine components viz., mold, plunger and chamber, as semisolid slurry is generally less erosive to these tools than liquid metal. Generally, thixotropic molding is more suitable than conventional die-casting processes in producing high quality molded parts with higher strength, better toughness and dimensional precision. In the past few years, thixotropic molding has been adopted rapidly by a variety of industries especially for molding magnesium alloy parts. In fact, ASM has recently listed thixotropic molding as a standard magnesium forming method (R.D. Carnahan, "Thixotropic Molding: Semisolid Injection Molding of Magnesium Alloys", Magnesium and Magnesium Alloys, ASM Specialty Handbook, Eds. M.M. Avedesiam and H. Baker, ASM International, pp. 90-97, 1999).

Prior to the present invention, thixotropic molding has been carried out using machines that resemble a thermoplastic injection-molding device as disclosed in U.S. Pat. No. 5,040,589. In this process, feedstock chips are fed into a reciprocating screw injection unit where it is externally heated and mechanically sheared by the action of a rotating screw. As the material is moved forward within the barrel, it is converted into semisolid slurry containing degenerated dendritic particles via partial melting and mechanical shearing, and is collected at a space between the injection nozzle and the screw tip. Once an appropriate amount of slurry has been accumulated, the screw is rapidly driven forward to inject the slurry into a mold cavity.

Although the existing procedure for thixotropic molding of semisolid alloys has been used successfully in the past, they suffer from a number of shortcomings and limitations including:

1. High cost of the extruder screw and barrel. Both the screw and barrel work under severe conditions – erosive attack from the semisolid metal, elevated operating temperatures, high injection pressure, high wear, and high thermal and mechanical fatigue; therefore, they can only be constructed using costly materials, such as maraging-type tool steels and cobalt-based alloys for processing magnesium alloys as disclosed in U.S. Pat. No. 5,996,679 and niobium-based alloys for processing aluminum or zinc alloys as disclosed in U.S. Pat. No.

5,819,839. Such materials have poor workability and machinability (U.S. Pat. No. 5,996,679). All of these mean that the extruder screw and barrel can increase manufacturing cost considerably and can consume a significant amount of maintenance cost as well since the screw must be regularly replaced due to wear and tear. It has been reported that a 600 ton capacity barrel made of nickel-based wrought Alloy 718 with a cobalt-based liner alone costs $150,000 (U.S. Pat. No. 6,059,012).

2. Extruder screw may not only raise the manufacturing and maintenance costs but may also cause operating problems, especially backward leakage of slurry. As indicated in U.S. Pat. No. 6,474,399, under high injection pressures, semisolid slurry may, via the clearance between the screw and the inner wall of the extruder barrel, leak backwards into and subsequently erode the shaft housing, and sometimes the driving mechanism of the screw.

3. The extruder barrel has to be opened and purged for alloy switching. This is unsafe when magnesium alloys are processed because semisolid slurries may combust when exposed to air.

4. A protective gas is needed in the extruder barrel to prevent oxidation; however, the gas may become trapped in the molded part, hence causing porosity (U.S. Pat. No. 5,501,266).

5. Semisolid slurries are made directly from dendritic feedstock using a so-called one-step method as disclosed in U.S. Pat. No. 4,694,882. However, depending on the shearing action provided by the screw, the dendritic grains may not be fully degenerated into globular shapes especially when the feedstock consists of a well-developed dendritic structure and when the volume fraction of solid phase in the slurry is relatively high. This may cause porosity, especially in thin walled parts.

In addition to the one-step semisolid slurry making method employed in the conventional thixotropic molding machine, which uses a shearing force to break up the dendritic network, semisolid slurries can also be obtained by a two-step method in which a dendritic-free (thixotropic) alloy is first prepared and then is reheated to a temperature between its solidus and liquidus temperatures (Flemings, M.C., Riek, R.G. and Young, K.P., “Rheocasting”, Materials Science and

Engineering, vol. 25, pp. 103-117, 1976). The two-step approach has been widely used for thixocasting.

There are two different processes for preparation of thixotropic or dendritic-free alloys – the first step in the two-step semisolid slurry making method. U.S. Pat. Nos. 3,902,544, 3,948,650, 3,954,455, 4,229,210 and 4,310,352 disclosed vigorous agitation processes where during casting an alloy is agitated while in the semisolid state to prevent formation of a dendritic network by either mechanical or electromagnetic stirring. U.S. Pat. Nos. 4,415,374, 5,133,811 and 6,120,625 disclosed strain induced and melt activated (SIMA) approaches, which use severe deformation and recrystallization to break-up dendritic structures.

BRIEF SUMMARY OF THE INVENTION

The present invention has been devised to overcome the foregoing shortcomings and limitations identified for the conventional thixotropic molding machine.

It is therefore a primary objective of the present invention to fulfill that need by providing a thixotropic molding method and apparatus for semisolid alloys, which is based on an extremely simple mechanism without use of a regular extruder screw or plunger.

It is another objective of the present invention to provide a method and apparatus for melting a terminal portion of a given length of a dendritic-free feedstock bar into semisolid slurry.

It is another objective of the present invention to provide a method and apparatus for injecting the above mentioned slurry into a mold cavity using the solid portion of the same feedstock bar mentioned above as an one-time extruder plunger.

It is another objective of the present invention to provide a method for automatically and periodically sealing the extruder barrel's heating zone so that oxidation of the slurry is prevented, thus, avoiding the use of a protective gas.

It is another objective of the present invention to provide a method for material switching without metal loss and preventing the opening and purging of the extruder barrel.

It is a further objective of the present invention to provide an improved thixotropic molding system that is more economical to manufacture, easier and safer to operate, more productive, and more suitable for producing high quality thin-walled parts.

These and other objectives are accomplished by providing a new thixotropic molding method comprised of feeding a dendritic-free feedstock bar into an extruder barrel, melting a terminal portion of the feedstock bar into a semisolid slurry by heating it to a temperature between its solidus and liquidus temperatures, and pushing the solid portion of the feedstock bar as an one-time "plunger" to inject the semisolid slurry into a mold cavity.

The feeding and pushing of the feedstock bar is carried out by a pair of unassisted wedges, which drives the feedstock bar toward the barrel during forward motion and then slides freely back.

The melting of a terminal portion of the feedstock bar is performed in a heating zone created by a series of band resistance heaters attached to the outer surface of the barrel. The length of the heating zone is changeable by the number of band heaters used. A cooling zone generated by a cooling ring with internal circulating coolant sits beside the heating zone. The heating zone is periodically sealed by solidification of the slurry leaked into the cooling zone at one end and in the discharge nozzle at the other end upon completion of each shot. As a result, no protective gas is needed within the extruder barrel.

In comparison with the methods and apparatus in the previous arts for thixotropic molding of semisolid alloys, the present invention results in a significant saving of both manufacturing and operational costs because: i) the extruder screw and its rotary driven mechanisms are removed, ii) the extruder barrel is built using less material, iii) the protective gas is eliminated, iv) the number of processing parameters are reduced, and v) the alloy switching procedures are simplified.

Most features of the conventional thixotropic molding machine are retained except that the present apparatus uses dendritic-free alloy bars as feedstock material. Although this may make

material recycling less convenient, it may provide the semisolid slurry with finer solid particles and a larger volume fraction of solid phase; thus, it is more suitable for producing net-shaped and bubble free parts. In addition, dendritic-free feedstock bars can be economically mass-produced by using vigorous agitation and/or SIMA processes.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic overview, partly in section, of the thixotropic molding apparatus according to one embodiment of the invention.

FIG. 2 is a front view of the thixotropic molding apparatus as shown in FIG. 1.

FIG. 3 is a sectional view of the extruder barrel.

FIG. 4 is a sectional view of the heating apparatus.

FIG. 5 is a sectional view taken on line A-A of FIG. 4.

FIG. 6 is a sectional view taken on line B-B of FIG. 4.

FIG. 7 is a schematic view of temperature distribution along a feedstock bar inside the extruder barrel.

FIG. 8a is a sectional view showing the formation of a one-time "plunger" at the beginning of a shot.

FIG. 8b is a sectional view showing the one-time "plunger" during the shot.

FIG. 9 shows the method of aligning two feedstock bars during loading.

DETAILED DESCRIPTION OF THE INVENTION

The thixotropic molding method taught in the present invention differs mainly from those in prior arts in that it is carried out without using a regular extruder screw or plunger so that the equipment and operational costs can be significantly reduced while retaining the most features of conventional thixotropic molding.

The new method involves feeding a dendritic-free feedstock bar into an extruder barrel, melting a terminal portion of the feedstock bar into a semisolid slurry by heating it to a temperature between its solidus and liquidus temperatures, and using the solid portion of the feedstock bar as an one-time "plunger" to inject the semisolid slurry into a mold cavity.

The new method can be realized by using a thixotropic molding machine **10** illustrated in FIG. 1. Machine **10** includes an extruder barrel **11** with a discharger nozzle **12**, which is in communication with a suitable cavity **51** through a sprue bushing **52** in a suitable two-part mold **50**. The mold, which may be of any suitable design, has a stationary half **53** fixed to a stationary platen **54** and a movable half **55** carried by a movable platen **56**.

Barrel **11** accommodates a dendritic-free feedstock bar **13** of a suitable metal alloy. The terminal portion of the bar **13** is converted into a semisolid slurry **16** by heating it to a temperature between its liquidus and solidus temperatures in a heating zone **61**, which is created by a series of band resistance heaters **15** attached to the outer surface of the barrel **11**. Separated by a heat insulator **17** is a two-part cooling ring **18** (only its bottom part is shown in FIG. 1) with circulating coolant (such as water) introduced through faucets **19** to form a cooling zone in the barrel **11**. The cooling zone freezes leaking slurry from the heating zone into a solid sealant **20**, effectively preventing air from entering the heating zone via the clearance between the bar **13** and the inner wall of the barrel **11**. On the other hand, a solid plug **14** is formed in the nozzle **12** from the residual slurry **16**, which prevents air from entering the barrel **11** via nozzle **12**. Thus, no protective gas is required in the heating zone of the barrel **11**.

Barrel **11** is supported by two stationary supports **41** at its rear and by a series of two-part supporting hoops **63** (only their bottom parts are shown in FIG. 1) in front. Both the stationary

supports 41 and the supporting hoops 63 are fixed to a barrel housing 40 that is supported by a pair of horizontal tie bars (not shown). Also mounted on the barrel housing 40 are two cylinders 42, which can, through rams 43, drive back and forth a movable clamp 44 comprised of a pair of wedges 45 touching with the surface of the feedstock bar 13. When the clamp 44 is driven toward the barrel 11, the wedges 45 automatically clip the bar 13 and force it into the barrel 11. By contrast, when the wedges 45 are moved away from the barrel 11, they automatically unclip the bar 13 and freely slide back.

A front view of machine 10 is shown in FIG. 2.

Operation of the thixotropic molding machine 10 involves converting a terminal portion of the feedstock bar 13, which is within the heating zone 61 of the barrel 11, into a semisolid slurry 16 using heat generated by band resistance heaters 15. Hydraulic cylinders 42 function at an appropriate time, when enough slurry 16 has been converted, to drive, via clamp 44, the bar 13 quickly toward the discharge nozzle 12. The pressure built up in the slurry 16 first ejects the plug 14 in the nozzle 12 and then injects the slurry into the mold cavity 51. The ejected plug 14 is trapped in the sprue bushing 52 for recycling. Following the completion of the injection, a length of the solid portion of the bar 13, which equals the stroke of the shot, is fed into the heating zone 61 to replenish the slurry. After a preset holding time during which the slurry in the cavity 51 solidifies, the clamp 44 retracts, releasing the pressure in the slurry 16 instantly. At the same time, residual slurry in the nozzle 12 is frozen into a plug 14 preventing drool and air from entering the barrel 11. After the molded part is removed and the mold 50 is re-closed, the thixotropic molding machine 10 is ready for the next shot.

Unlike that in a conventional thixotropic molding machine, barrel 11 has only its frontal portion in contact with the corrosive semisolid slurry 16 and subject to an elevated temperature and injection pressure. To minimize its manufacturing cost, therefore, barrel 11 can be designed as a tri-metallic cylinder, which, as illustrated in FIG. 3, comprises of a bimetallic portion 22 and a monometallic portion 25 joined by welding 26. The bimetallic portion 22 comprises of an outer shell 23 providing strength and fatigue resistance at operating temperatures and a liner 24 that is shrunk-fit onto the inner surface of the outer shell 23 preventing corrosion caused by the slurry 16. Suitable materials for making the outer shell 23 and liner 24 are dependent on the type of feedstock

alloy used. Table 1 lists several available materials for Al, Mg and Zn feedstock. Since it is neither in contact with the semisolid slurry **16** nor subject to shot pressure and high temperatures, the monometallic portion **25** can be made of any suitable metallic material. Two grooves **31** on the monometallic portion **25** are for communication with stationary supports **41**. Flange **27** joined with the outer shell **23** via welding **21** is for mounting the nozzle **12**. Flange **28** is for housing an O-ring **29**, which is used to prevent air from entering the barrel **11** via the clearance between the bar **13** and the inner wall of the barrel **11**. In this way, the oxidation on the surface of the high temperature region of bar **13** adjacent to the heating zone **61** can be eliminated. The barrel **11** can be washed with a protective gas, introduced through a faucet **30**, during first-time use after each shift to expel the remaining air from the barrel to further prevent oxidation, especially during the first few shots. The outer shell **23** has a typical thickness of 10 mm and may not be strong enough to support the shot pressure; therefore, supporting hoops **63** are used to provide extra strength for the barrel **11**.

Table 1 – Materials suitable for making outer shell **23** and liner **24**

Feedstock alloy	Suitable materials for making	
	Outer shell **23**	Liner **24**
Al, Zn	Nickel-based alloys: Alloy 718, Alloy 909.	Nb-based alloy: Nb-30Ti-20W.
Mg	Nickel-based alloy: Alloy 718.	Cobalt-based alloys: Stellite 6, Stellite 12.

FIG. 4 illustrates one embodiment of the heating apparatus **60**, which consists of a heating zone **61** and a cooling zone **62**. As mentioned previously, the heating zone **61** is created by a series of band resistance heaters **15** attached to the outer surface of the barrel **11**. The cooling zone **62** is generated by a two-part cooling ring **18** with circulating coolant **72** inside. Separating the heating and cooling zones is a plate **17** made of a heat insulating material. Each band resistance heater **15** associated with the heating zone **61** is enveloped by a groove **64** made on the inner surface of a supporting hoop **63**, of which the rims are in contact with the outer surface of the barrel **11** to withhold the shot pressure.

As detailed in FIG. 5, a supporting hoop **63** has a top **63a** and bottom **63b**, which are fastened to the base of the barrel housing **40** by bolts **65**. An outlet **66** is made at the middle of the

top **63a**, through which wiring is conjugated between the terminals **67** of a band heater **15** and a terminal bus **68**, which is fixed to the top of the cover **69** of the heating apparatus **60**. A vertical groove is made at the middle of the both sides of the top **63a**, which forms a suitable thermocouple outlet **70**, through which a thermocouple can be placed to the outer surface of the barrel **11** for temperature control (FIG. 4). Both the top **63a** and bottom **63b** may be made of the same material as the outer shell **23**.

FIG. 6 illustrates one embodiment of the cooling ring **18** comprising of a top **18a** and a bottom **18b**, which are fastened to the base of the barrel housing **40** by bolts **71**. Circulating coolant **72**, which is introduced through faucets **19**, cools the cooling ring **18**. The cooling ring **18** is separated from the heating zone **61** by a heat insulator **17**. Both the top **18a** and the bottom **18b** may be made of a suitable material with high heat conductivity.

Also shown in FIG. 4 is the nozzle **12** fastened to the barrel **11**. Three band resistant heaters similar to those used in the heating zone **61** are attached to the terraced surfaces of the nozzle **12** to maintain constant temperature with the heating zone **61**. The nozzle **12** may be made of the same material as the liner **24**.

FIG. 7 illustrates the temperature distribution along the feedstock bar **13** (including the converted slurry **16**) at the moment prior to an injection. It can be seen that a constant temperature between the liquidus and solidus temperatures of the feedstock alloy is maintained for the heating zone (including the nozzle). For a given feedstock alloy, the constant temperature determines the volume fraction of the solid phase in the slurry **16**. At the region of the nozzle tip where no heaters are installed, the temperature declines below solidus resulting in the formation of a solid plug **14**. On the other hand, the temperature within the cooling zone is reduced rapidly to below the solidus temperature leading to formation of a solid sealant **20**, which effectively seals off the clearance between the feedstock bar **13** and the inner surface of the barrel **11**. Beyond the cooling zone, the temperature of the bar **13** is gradually reduced to room temperature.

FIG. 8a illustrates the formation of a one-time "plunger" at the beginning of a shot. At such a moment, stress within the feedstock bar **13** is quickly increased due to the friction between the sealant **20** and the inner surface of the barrel **11**. The stress will first exceed the yielding point of

the solid tip of the bar **13** attaching to the slurry **16**, which is the most soft solid material in the bar **13**. As a result of the plastic deformation, a bulge **80** is formed. While the bar **13** and its associated bulge **80** are forced to move forward, they act as a one-time plunger to raise the pressure in the slurry **16** until the plug **14** is ejected. Following the ejection, the one-time plunger (i.e. the feedstock bar) is quickly moving toward the discharge end of the barrel **11**, and hence slurry is injected into a mold cavity as shown in FIG. 8b. After completion of the shot, a length of the bar **13**, including the bulge **80**, equaling the stroke of the shot will now be inside the heating zone of the barrel **11**, and will in turn be heated and converted into semisolid slurry for the next shot.

The diameter tolerance of the Bar **13** with the inner diameter of the barrel **11** is typically 1 mm. Its surface finish should be smooth enough to permit good contact with the O-ring **29**. Bars prepared using a continuous casting machine or hot extruder can satisfy these requirements. The length of the feedstock bar **13** is typically 2-5 meters, but can be as long as the space and handling permits. In general, a longer feedstock bar gives more molding shots per bar loading and therefore, increases productivity. A sensor (may be attached with the clamp **44**; not shown) can be used to detect the end of the feedstock bar **13**. Bar loading can be accomplished by placing the alignment-convex **82** of a new bar **13b** behind the alignment-concave **81** of the current bar **13a** as shown in FIG. 9.

Owing to the low cost of the barrel **11**, it may now be affordable to supply one or more spare extruder barrels for a given molding machine. Thus, alloy switching may be simply accomplished by replacing the current barrel with another preloaded with a feedstock bar of a different alloy. To remove the current barrel, the following procedure is carried out: 1) open the heating apparatus cover **69**, 2) unfasten all barrel supporting hoops **63**, 3) unfasten the cooling ring **18**, 4) detach wires from all band heater terminals **67**, 5) unfasten the barrel supports **41**. The following procedure is carried out after a barrel is loaded: 1) fasten the barrel supports **41**, 2) wire all band heater terminals **67**, 3) fasten all barrel supporting hoops **63**, 4) fasten the cooling ring **18**, 5) close the heating apparatus cover **69**. Alloy switching in this way requires no barrel opening and purging and is, therefore, easier, safer and more time efficient in comparison with methods used in conventional thixotropic molding machines processing magnesium alloys as described in Japan Pat. No 6,474,399.

The volume of the slurry **16** in the barrel **11**, which determines the maximum weight of a molded part that can be made from one shot using the thixotropic molding machine **10**, can be calculated from the inner diameter of the barrel **11** and the maximum length of the heating zone **61**. A typical machine with a standard barrel having an inner diameter of 50 mm and a maximum of 400 mm in heating zone length is capable of molding a Mg part of 1.39 kg, a Al part of 2.12 kg, or a Zn part of 5.6 kg. Larger parts can be produced by increasing either the barrel's diameter or the length of the heating zone or both. However, increasing the barrel's diameter (thus, the diameter of the feedstock bar) may increase the heating time needed to convert the solid feedstock into semisolid slurry leading to an elongated inter-shot time. On the other hand, increasing the length of heating zone is limited by the length of the heating apparatus **60**, but the inter-shot time would not be lengthened.

The length of the heating zone **61** can be altered by changing the number of supporting hoops **63** (thus, the number of band heaters **15**), which may be from a minimum of 1 to a number limited by the length of the heating apparatus **60**. The width of a typical supporting hoop **63** is usually 2 inches and that of its associated band heater **15** is 1.5 inches.

Band resistance heaters **15** used for the heating zone **61** and for the nozzle **12** can be controlled individually, by group, or as a whole. The individual or group control is preferred for easily obtaining a uniform temperature distribution. In general, better temperature control with faster response can be achieved in the present invention because the barrel **11** has a much thinner wall than that used in conventional thixotropic molding machines.

To ensure the quality of molded parts, the inter-shot time should be equal to or greater than a time period (denoted by t_p) during which a suitable amount of semisolid slurry can be generated to fully fill the mold cavity **51**. Although t_p can be determined by trial and error, the equation below provides a more flexible and accurate alternative.

$$t_p = \frac{t_u W}{\pi \rho r^2 L} \qquad \text{Eq. 1}$$

where, t_u is the uniformity time at which a section of the bar **13** has reached a radial temperature uniformity since entering the heating zone **61**, W is the weight of the molded part(s) (including runner spreaders), ρ is the density of the feedstock, r is the inner radius of the barrel **11**, and L is the length of the heating zone **61**; all in SI units. The uniformity time can be readily calculated by solving the following equation of heat conduction using a finite element or a finite difference approach:

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) \qquad \text{Eq. 2}$$

where, T is temperature, t is time , κ is the heat conductivity of the feedstock.

The stroke of a shot (denoted by S) can be calculated by:

$$S = \frac{W}{\pi \rho r^2} \qquad \text{Eq. 3}$$

During a shot, the feedstock bar **13** should be initially pushed to move at its maximum speed and to remain at such speed for most of the shot, but must be slowed just before reaching full stroke to reduce impact and rebound as the mold cavity **51** is filled.